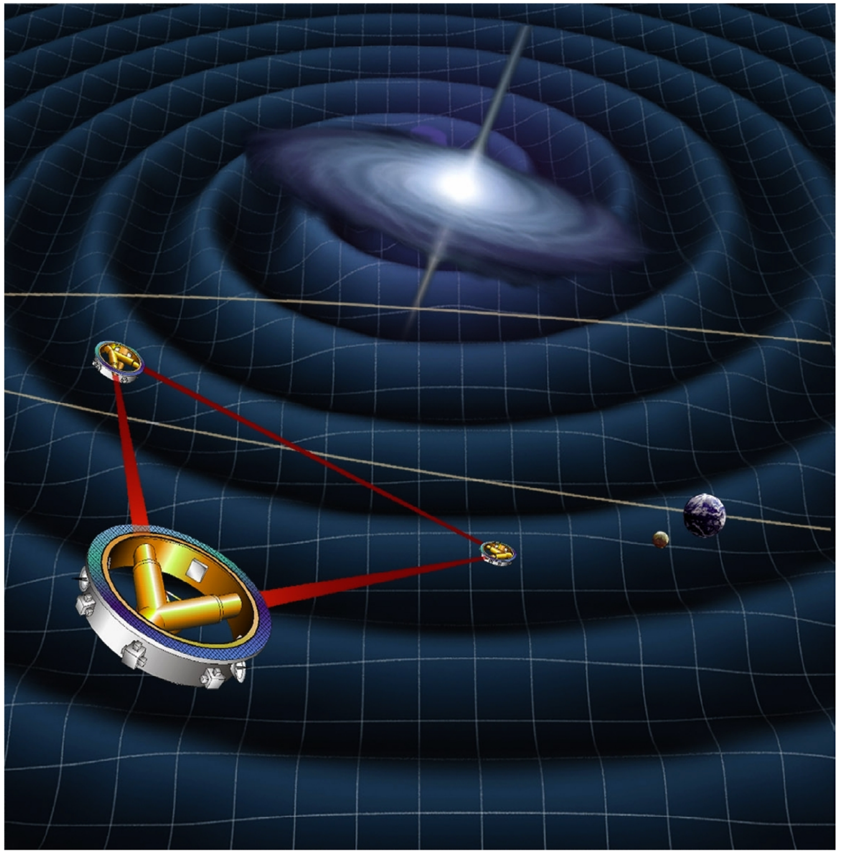
LISA Science and Concept

Robin T. Stebbins

LISA Overview

Beyond Einstein: From the Big Bang to Black Holes



- The Laser Interferometer Space Antenna (LISA) is a joint ESA-NASA mission to design, build and operate a space-based gravitational wave detector
- The 5 million kilometer long detector will consist of three spacecraft orbiting the Sun in formation
- Space-time strains induced by gravitational waves are detected by measuring the separation of fiducial masses with laser interferometry
- LISA is expected to detect signals from merging supermassive black holes, compact stellar objects spiraling into supermassive black holes in galactic nuclei, thousands of close binaries of compact objects in the Milky Way and possibly backgrounds of cosmological origin

A New Approach to Astrophysics

- Gravity is the dominant force in the Universe
  - Creates planets, stars, clusters of stars, galaxies, clusters of galaxies and compact objects
- Compact objects
  - Mass aggregations more dense than normal stars
  - Compact objects come in a wide range of sizes
  - Changing mass distributions make gravitational waves
- (Mostly) Binary systems (Big bad billiard balls of the Universe)
  - Supermassive black holes from galaxy mergers
  - Building up supermassive black holes from mergers of intermediate/seed mass black holes
  - Big black holes capturing small compact objects
  - Stellar-sized binaries
  - “Other”

What Are Gravitational Waves?

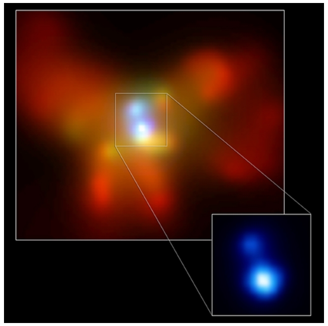
- Electromagnetic analogy
  - The radiative form of gravity, analogous to radio or light waves
  - Mass is the “charge” (no negative charge)
- What are they?
  - A strain in space-time. Propagating ripples in space-time.
  - Fractional length change, $\Delta L/L$
  - Typical strains are very small, even with large masses. (Space-time is stiff. Coupling between matter and waves is very weak. Very little interaction with intervening matter.)
  - Measure ΔL, so prefer big L
  - Propagate at the speed of light
  - Quadrupolar with two polarizations, no dipolar.
- How are they made
  - Changing mass quadrupole
  - Time varying mass distributions
- How are they felt
  - Ring of masses
  - Corks on the pond

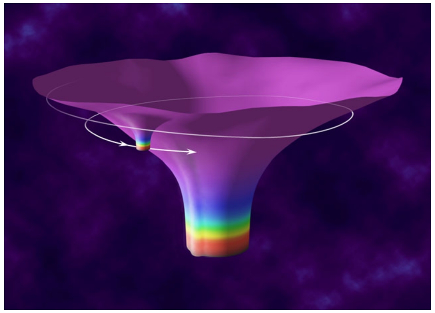
LISA Science Goals & Sources

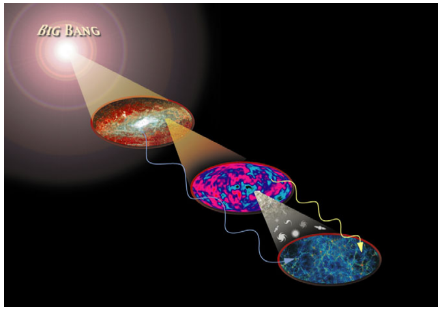
Beyond Einstein: From the Big Bang to Black Holes

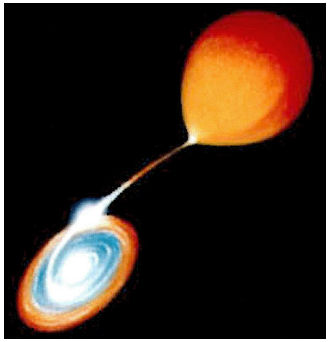
- Determine the role of massive black holes in galaxy evolution
- Make precision tests of Einstein's Theory of Relativity
- Determine the population of ultra-compact binaries in the Galaxy
- Probe the physics of the early universe

- Merging supermassive black holes
- Merging intermediate-mass/seed black holes
- Gravitational captures
- Galactic and verification binaries
- Cosmological backgrounds and bursts



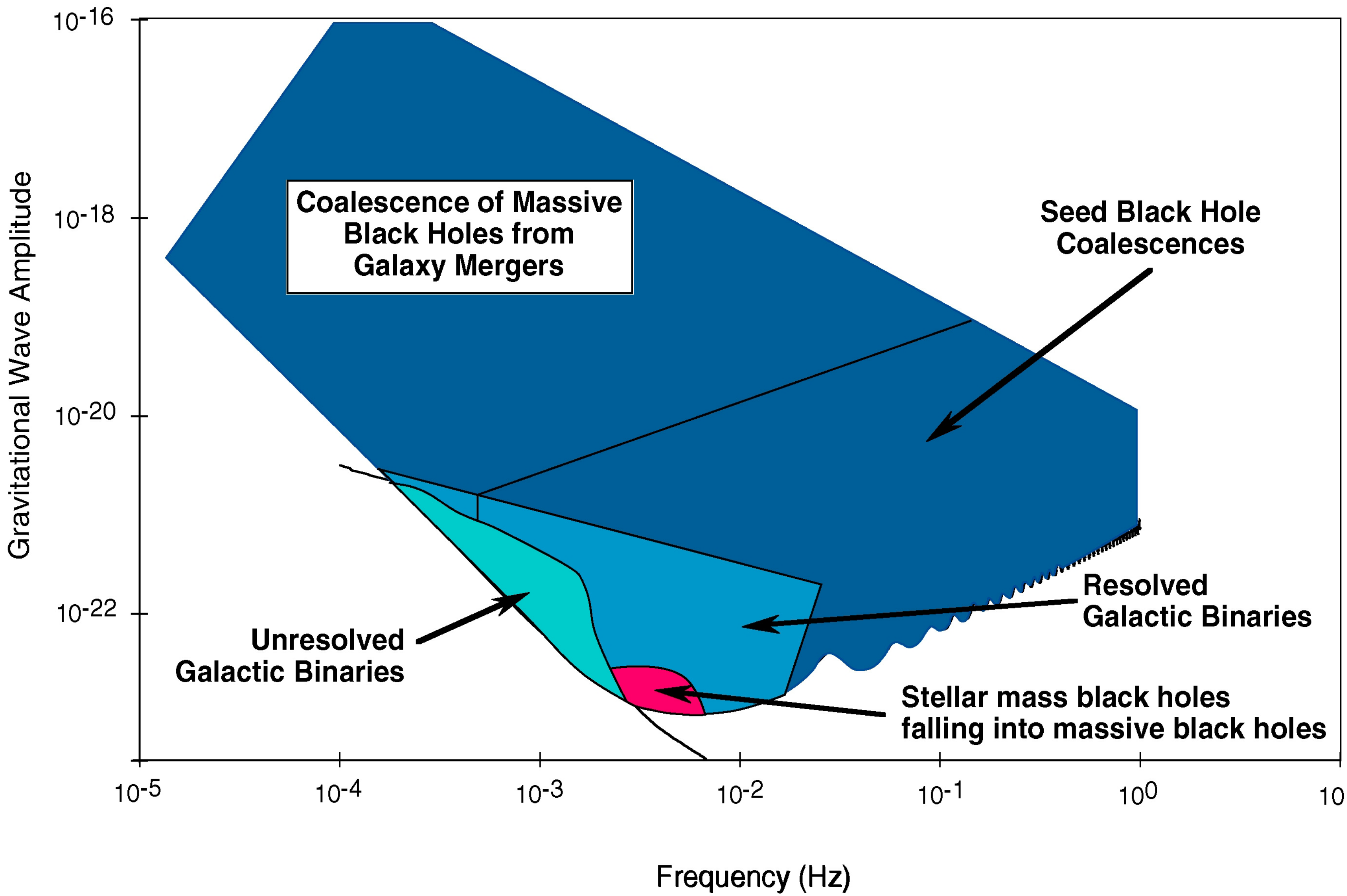






Sensitivity and Sources

Beyond Einstein: From the Big Bang to Black Holes



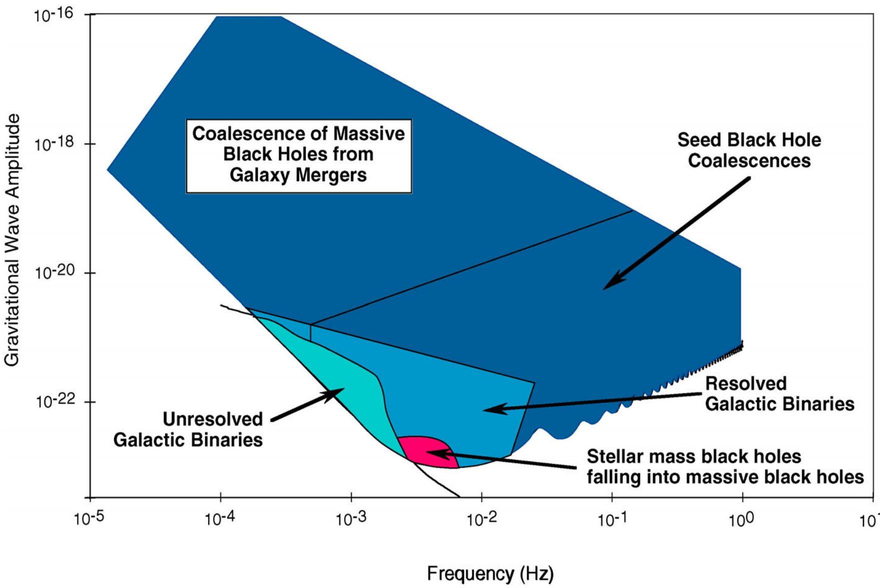
How Do You Detect GWs?

- A strain in space-time, propagating ripples
- Put out an array of reference masses to move with space-time.
- Monitor changes in separation between the array of masses, with requisite sensitivity
- Protect masses from disturbances that would mask the gravitational waves
- Other detection methods:
  - Resonant detectors
  - Ground-based interferometers: LIGO, GEO, Virgo, TAMA, ACIGA
  - Other space-based: spacecraft ranging

Measurement Parameters and Sensitivity

Beyond Einstein: From the Big Bang to Black Holes

- Measurement Parameters:
  - Acceleration requirement
  - Measurement sensitivity requirement
  - Arm length
  - Integration time
- How measurement parameters affects sensitivity
- Sensitivity curve



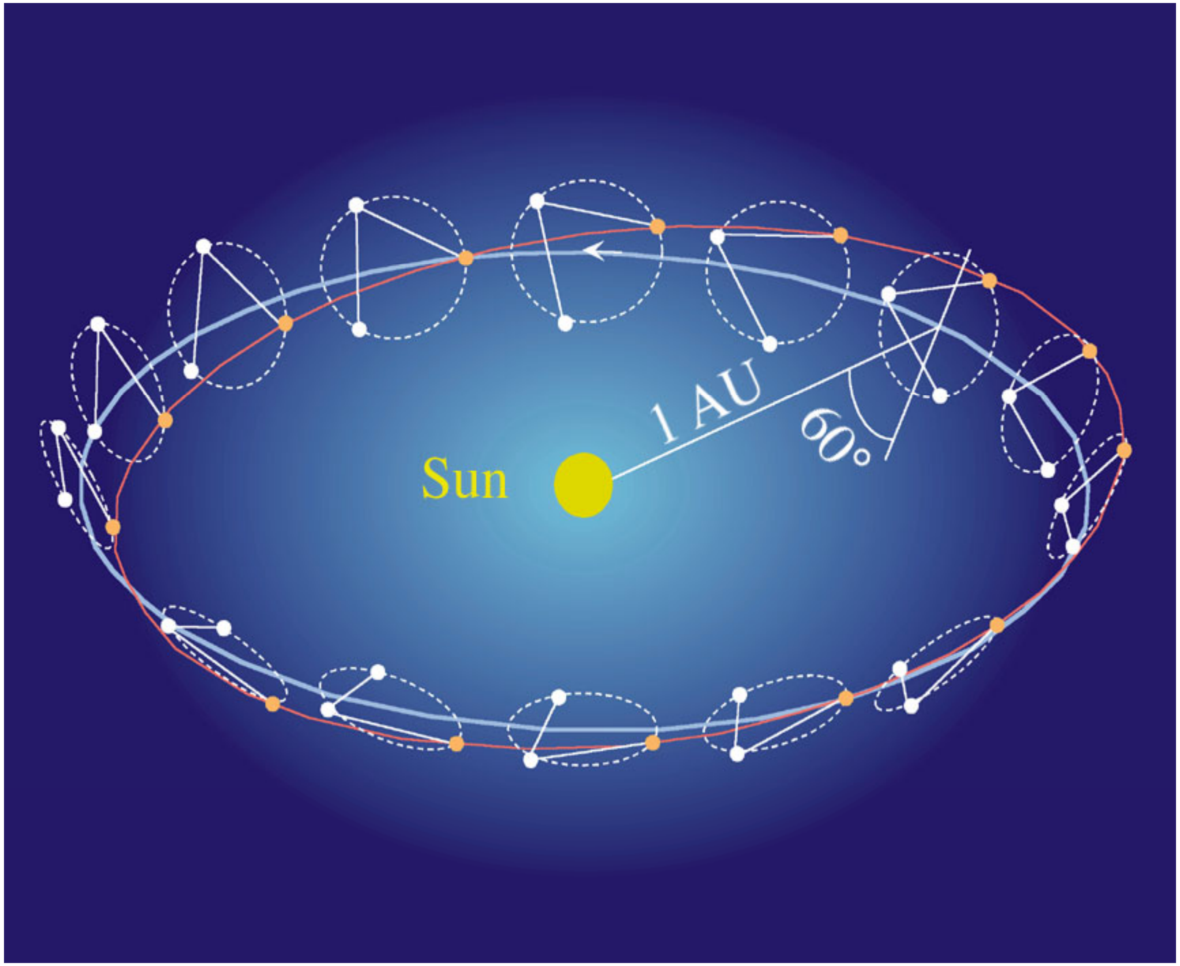
Measurement Concept

Beyond Einstein: From the Big Bang to Black Holes

- Measure time-varying strain in space-time by interferometrically monitoring changes in three 5 million kilometer long arms
- The three arms:
  - Form an equilateral triangle
  - Are defined by six proof masses, located in pairs at the vertices of the triangle
  - Are monitored interferometrically to achieve a measurement bandwidth from 10^{-4} to 10^{-1} Hz
- A spacecraft at each vertex houses the two proof masses and the interferometry equipment. The formation orbits the Sun 20° behind the Earth.
- The proof masses are protected from disturbances by careful design and “drag-free” operation (i.e., the mass is free-falling, but enclosed and followed by the spacecraft)
- Lasers at each end of each arm operate in a “transponder” mode. Optical path difference changes, laser frequency noise, and clock noise are determined
- Three arms measure both polarizations of quadrupolar waves. Source direction is decoded from amplitude, frequency, and phase modulation caused by annual orbital motion.

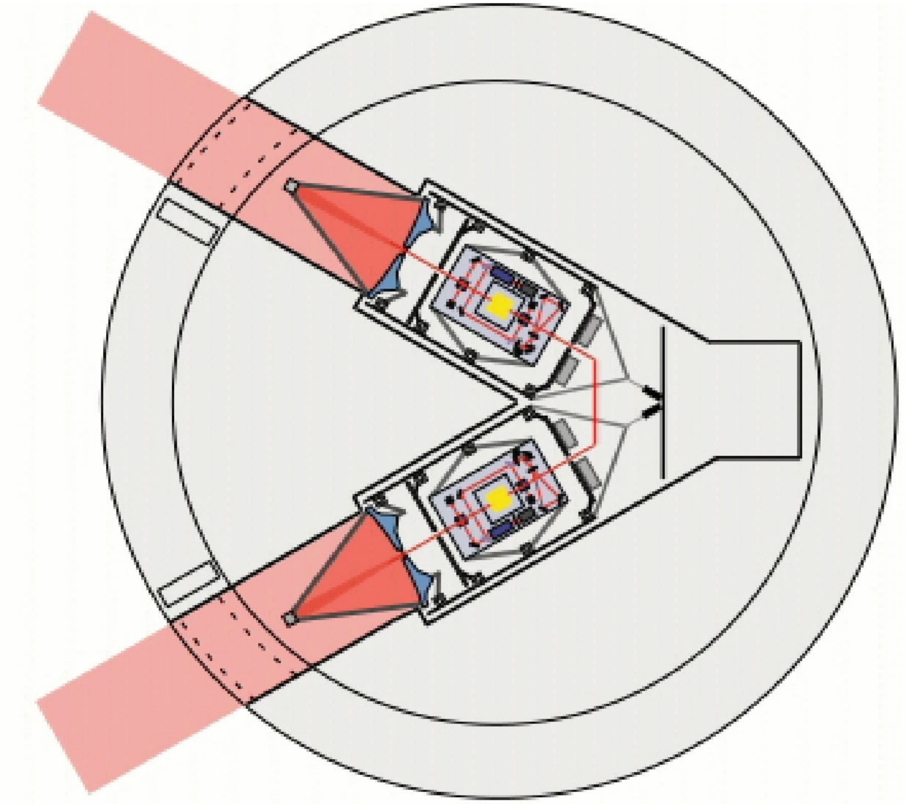
Orbit

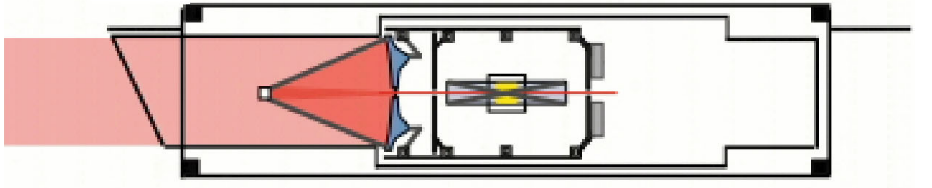
- Formation trails Earth by 20°; approximately constant arm-length
- Spacecraft have constant solar illumination and benign environment



Disturbance Reduction System

- GRS:
  - Proof mass
  - Electrostatic sensing
  - Electrostatic actuation
  - Charge control
- Microthrusters:
  - Liquid metal ion emitters
  - Neutralizers
- Control Laws
- Integrated spacecraft / payload design features

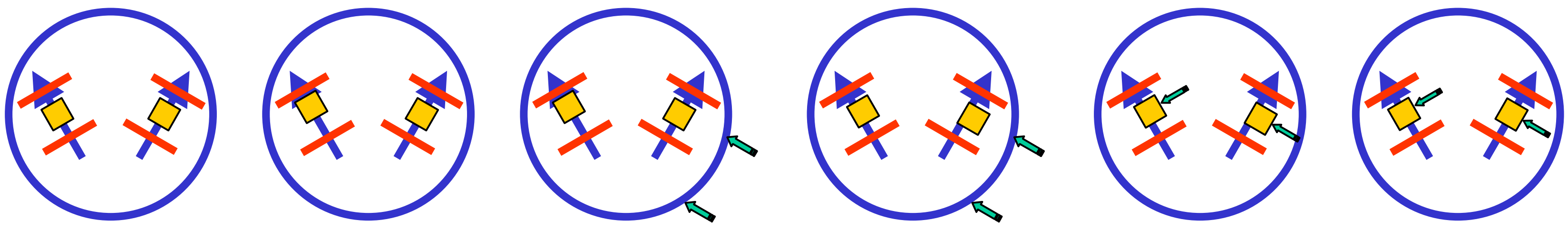




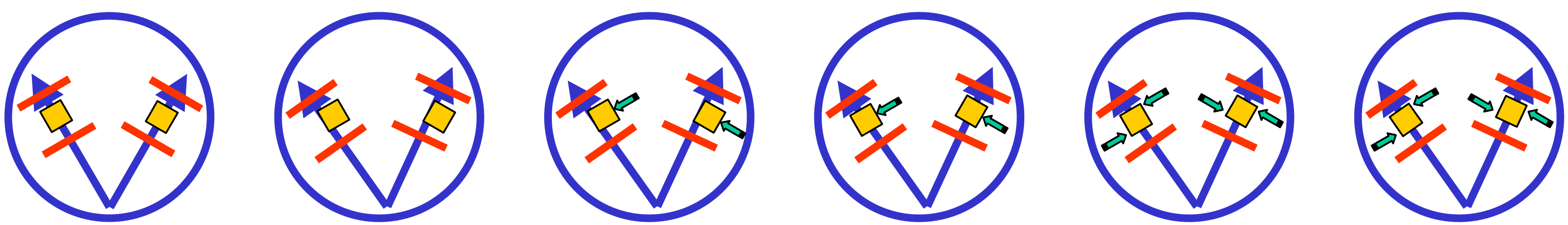
DRS Operation

How the disturbance reduction system follows two proof masses with one spacecraft?

Left hand proof mass moves along measurement direction:

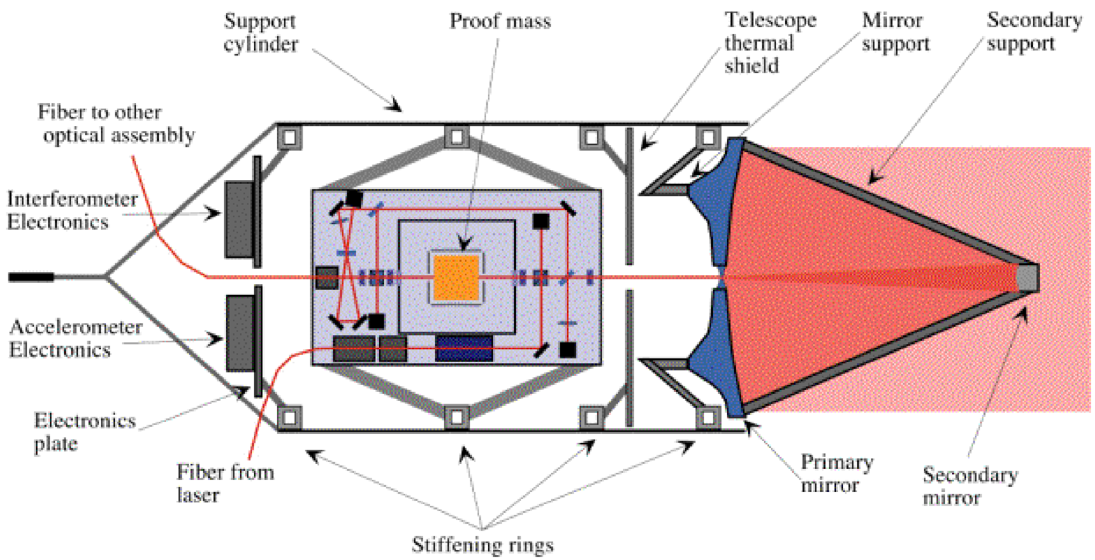


Spacecraft rotates with respect to the proof masses:



Interferometry Measurement System

Beyond Einstein: From the Big Bang to Black Holes



- 30 cm, *f*/1 transmit/receive telescope
- Optical bench with interferometry optics, laser stabilization
- Gravitational reference sensor
- 1 W diode-pumped, Yb:YAG laser, plus spare
- Fringe tracking and timing electronics, including ultra-stable oscillator
- System for comparing phase information from two arms

IMS Cartoon

- The distance monitoring system is a continuous ranging system using optical frequencies, like spacecraft tracking
- The ranging system senses:
  - Inter-spacecraft doppler motions
  - Temporal variations of laser frequency
  - Time variations of the optical pathlength between proof masses
- The phasemeter measures the accumulated phase as a function of time
- The science signal appears as a phase modulation in the beat signal

Requirements

Source	Spectral Amplitude (1×10^{-4} Hz)	Spectral Amplitude (1×10^{-3} Hz)	Spectral Amplitude (5×10^{-3} Hz)	Spectral Amplitude (1×10^{-2} Hz)	Observation Time (Yrs)
Merging supermassive black holes	4×10^{-17}	8×10^{-19}	1×10^{-19}	N/A	5 (3 arms required)
Intermediate-mass/seed black holes	N/A	3×10^{-19}	2×10^{-20}	2×10^{-20}	1
Gravitational capture from nuclear star clusters	N/A	3×10^{-19}	1×10^{-20}	1.5×10^{-20}	3
Galactic binaries and verification binaries	N/A	3×10^{-19}	3.5×10^{-20}	N/A	2
Cosmological backgrounds	N/A	N/A	N/A	N/A	1 (3 arms required)
Overall Requirement	**4×10^{-17}**	**3×10^{-19}**	**1×10^{-20}**	**1.5×10^{-20}**	**5** (3 arms required)

Table D-1 Derived Science Requirements

Parameter	Requirement	Error Estimate	Margin
Arm length	5×10^{6} km	N/A	N/A
Spurious acceleration (per proof mass)	3×10^{-15} m/s²/√Hz, 0.1 to 1 mHz	2.0×10^{-15} m/s²/√Hz, 0.1 to 1 mHz	119%
Measurement sensitivity (round trip)	4×10^{-11} m/√Hz, 1-100 mHz	2.8×10^{-11} m/√Hz, 1-100 mHz	53%
Integration time	1 year	N/A	N/A

Mission Performance Requirements, Error Estimates, Margins

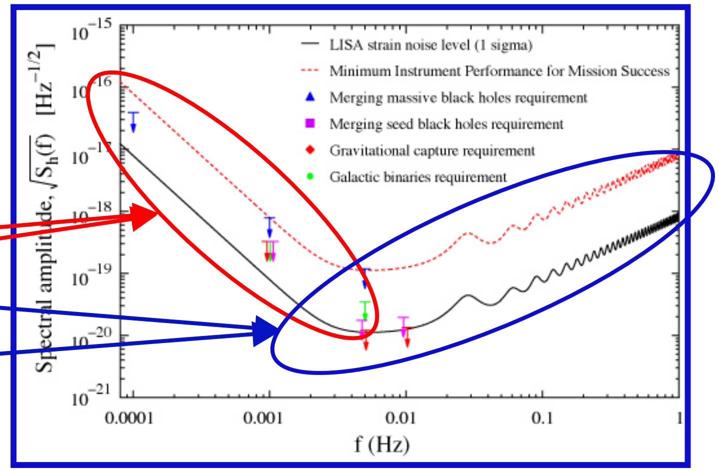


Fig. D-7 Instrument Performance and Science Requirements

Requirements

Beyond Einstein: From the Big Bang to Black Holes

- Acceleration Noise: $\times 10^{-16}\ m/s^2/\sqrt{Hz}$

	Allocation	Error Estimate	Margin
Cross-talk	10.0	7.9	26%
Random charging	10.0	7.0	43%
Thermal distortion of S/C	10.0	5.0	100%
Residual gas	10.0	3.0	233%
Back action from position sensing	10.0	2.5	300%
Dielectric losses	10.0	2.4	317%
Fluctuating applied voltages	5.0	2.0	150%
Magnetic damping	5.0	2.0	150%
Magnetic remanence	5.0	2.0	150%
Fluctuating applied voltages	5.0	2.0	150%
Remainder of Noise force on S/C	5.0	1.6	218%
Remainder of Magnetics S/C	5.0	1.0	400%
Gravity noise from S/C motion	5.0	1.0	400%
Radiation pressure	3.0	1.0	200%
Other small effects	10.8	2.9	266%
Quadratic Sum	**30.00**	**13.71**	**119%**

Requirements

- Displacement Noise:

		x10^-12 m/¦Hz		
Effect	Number	Allocation	Error Estimate	Margin
Shot noise (photon statistics)	4	11.0	10.0	10%
Laser beam pointing noise	4	10.0	5.0	100%
Oscillator frequency noise	1	10.0	5.0	100%
Residual laser frequency noise	1	10.0	5.0	100%
Phase measurement and transponder lock	4	5.0	2.5	100%
Stray light effects	4	5.0	2.5	100%
Other substantial effects	32	3.0	1.5	100%
Combined Total (quadratic sum with Number multiplier)		**39.6**	**25.9**	53%

Summary

- LISA promises extraordinary science:
  - Guaranteed to see thousands of gravitational wave sources
  - Most violent events in the Universe since the Big Bang
  - Can see back the “Dark Ages” of the Universe
- The LISA mission concept applies known technologies in novel ways:
  - Drag-free technology
  - Spaceborne accelerometry
  - Interferometric ranging
  - The “instrument” is the constellation of spacecraft